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Supplementary Materials

Assessing the Scale Effects of Dynamics and Socio-Ecological Drivers of Ecosystem Service Interactions in the Lishui River Basin, China

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This file includes:

1. Ecosystem service (ES) assessments (including Tables S1 – S6)
2. Characteristics of ES bundles
3. Proportion of land use types (Figure S1)

1. Ecosystem service (ES) assessments

(i) Carbon storage (CS)

CS is one of the primary regulating services referring to the amount of carbon stored by terrestrial ecosystems, which is relevant to ecosystems' capacities to cope with climate change [1-3]. We utilized the Carbon Storage and Sequestration module in InVEST model to quantify CS by combining LULC with four major carbon pools in the ecosystems, namely, above biomass, underground biomass, soil carbon, and dead matter [4,5].

$$C_tot = C_above + C_below + C_soil + C_dead \quad (S1)$$

where C_tot is total CS, C_above is carbon in aboveground biomass, C_below is carbon in belowground biomass, C_soil is carbon in the soil, and C_dead is carbon in dead matter. We summed up carbon pool data for each LULC type in each grid cell to obtain CS at the grid scale. The carbon density of each LULC type in carbon pools (Table S1) was determined by referring to "A dataset of carbon density in Chinese terrestrial ecosystems (2010s)" [6] and comparable assessment cases [7].

Table S1. The carbon density of each land use/land cover ($Mg \cdot ha^{-1}$).

Land use/land cover	C_above	C_below	C_soil	C_dead
Cropland	2.66	0.4	92.04	0
Forest	44.6	11.1	106.1	1.9
Grassland	0.43	4.4	85.4	0.08
River	0.6	79	81.1	0
Lake	0.6	79	81.1	0
Bottomland	0.6	79	81.1	0
Urban land	9.33	2.33	94.13	0
Other land	0	0	45.11	0

Note: C_above is carbon density in aboveground biomass; C_below is carbon density in belowground biomass; C_soil is carbon density in the soil; C_dead is carbon density in dead matter.

(ii) Habitat quality (HQ)

HQ refers to the ability of ecosystems to provide conditions suitable for the persistence of individuals and populations [4,8], which is one of the important supporting services. High-quality habitats can provide more resources for population survival to better support different levels of biodiversity. We modeled HQ using the InVEST model, which calculates habitat quality by combining the stress intensity of different land use/land cover (LULC) types and their sensitivity to threat factors. HQ was calculated using the following formula [4]:

$$Q_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right) \quad \text{(S2)}$$

where Q_{xj} is HQ value of grid x; H_j is the habitat suitability of LULC type j; D_{xj} is the habitat degradation degree of grid x; z is a scaling parameter (2.5 in InVEST); k is the half-saturation constant, which was set at 0.05. Except for LULC data, the threat factor table and sensitivity table are required in the InVEST model (Table S2 and Table S3). The coefficients of threat factors, values of habitat suitability, and sensitivity of habitat types to threat factors were referenced from the InVEST User Guide [4,9] and the study in similar areas [7,10].

Table S2. The sensitivity of habitat types to each threat factor [7].

Threat factors	Maximum distance of influence	Weights	Spatial decay types
Urban land	11	0.8	exponential
Rural settlement	5	0.6	exponential
Cropland	6	0.5	exponential
Main road	10	1	linear
Railway	9	0.8	linear

Maximum distance of influence: The distance of influence of each threat factor on habitat integrity. Weights: The degree of influence of each threat factor on habitat integrity compared to other threat factors, with a weight range from 0 to 1.

Table S3. Habitat suitability and sensitivity of habitat types to each threat factor [4,9,10].

Habitat type	**Habitat suitability score**	**Sensitivity to threats**					
		Urban land	**Rural settlement**	**Cropland**	**Road**	**Railway**	**Other built-up land**
Cropland	0.5	0.5	0.4	0.3	0.2	0.1	0.6
Forest	1	0.7	0.8	0.3	0.6	0.5	0.8
Grassland	0.7	0.7	0.7	0.3	0.4	0.4	0.6
River	0.9	0.8	0.7	0.6	0.6	0.5	0.9
Lake	0.9	0.8	0.6	0.5	0.6	0.4	0.9
Bottomland	0.6	0.8	0.7	0.6	0.6	0.5	0.7
Urban land	0	0	0	0	0	0	0.2
Rural settlement	0	0	0	0	0	0	0.7
Other built-up land	0	0.7	0.6	0	0	0	0
Bare land	0	0.3	0.2	0	0	0	0.3

(iii) Soil conservation (SC)

The InVEST Sediment deliver Ratio module uses the Revised Universal Soil Loss Equation (RUSLE) to calculate the amount of soil erosion within a cell [11]. In the RUSLE, the soil conservation amount of the unit is determined by comparing the difference

between the bare land surface and the consideration of vegetation coverage and management measures . The calculation formula is as follows:

$$SC_x = RKLS_x - USLE_x \quad \text{(S3)}$$

$$RKLS_x = R_x \times K_x \times LS_x \quad \text{(S4)}$$

$$USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x \quad \text{(S5)}$$

where SC_x represents the soil conservation amount of the grid x(t·hm^{-2}·yr^{-1}), $RKLS_x$ and $USLE_x$ representing the potential erosion amount and the actual erosion amount of the grid x; $R_x$is the rainfall erosion factor (MJ·mm(hm^2·hr·yr)$^{-1}$),$K$is the soil erosion factor(t·hm^2·hr(MJ·hm^2·mm)$^{-1}$), LS is the slope length and slope factor(dimensionless), C and P are vegetation coverage factor and management measure factor(dimensionless), respectively.

The rainfall erosivity factor(R_x) is calculated according to the monthly and annual precipitation. The soil erosivity factor(K) is calculated according to the soil texture according to the EPIC formula [12]. The calculation formula is as follows:

$$R_x = \sum_{i=1}^{12} 1.735 \times 10\left(1.5 \lg \frac{P_{ix}^2}{P_x}\right) - 0.8188 \quad \text{(S6)}$$

$$K = \{0.2 - 0.3exp\left[-0.0256SAN\frac{1-SILT}{100}\right]\}\left(\frac{SILT}{CLAY+SILT}\right)^{0.3} \times \left[1.0 - \frac{0.25OC}{OC+exp(3.72-2.95OC)}\right] \times \left[1.0 - \frac{\frac{0.7\times(1-\frac{SAND}{100})}{(1-\frac{SAND}{100})+exp(-5.51+22.9\times(1-\frac{SAND}{100}))}}{}\right] \times 0.1317 \quad \text{(S7)}$$

where P_x represents the rainfall of the grid x(mm), and P_{ix}^2 represents the precipitation of the grid x in month i; $SAND$、$SILT$、$CLAY$、OC indicates the sand content(%), silt content(%), clay content(%) and organic carbon content(%).

The length-slope factor calculated according to the following formula:

$$L = \left(\frac{\lambda}{22.13}\right)\begin{cases} m = 0.5 & \theta > 9\% \\ m = 0.4 & 3\% < \theta < 9\% \\ m = 0.3 & 1\% < \theta < 3\% \\ m = 0.25 & \theta \le 1\% \end{cases} \quad \text{(S8)}$$

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 9\% \\ 16.8\sin\theta - 0.50 & 9\% < \theta < 18\% \\ 21.91\sin\theta - 0.96 & \theta \ge 18\% \end{cases} \quad \text{(S9)}$$

where λ is the slope length(m), m is the slope length index(dimensionless), and θ is the percentage of the slope.

$$C = \begin{cases} 1, f = 0 \\ 0.6508 - 0.3436\lg f, 0 \le f \le 75\% \\ 0, f \ge 75\% \end{cases} \quad \text{(S10)}$$

C and P are vegetation coverage factor and management measure factor respectively. The determination of the two factors refers to previous studies and the InVEST user guide, and corresponding modifications are made according to the situation in this study area.

The soil retention model parameter table is required in the InVEST model (Table S4). The management factor (P) is the ratio of soil loss after adopting specific measures to the soil loss when planting along the slope, reflecting the difference in soil loss caused by different vegetation management measures. Its range is [0-1]. In this study, the values are based on previous research results and studies in similar regions [13]. The vegetation cover factor (usle_c) is calculated using the vegetation coverage according to formula (10). The management factor (usle_p) is obtained based on the literature [13]. The sediment retention rate (sedret_eff) is obtained based on the model database and corrected using literature from regions similar to the study area [14] (Table S4).

Table S4. Parameter table of soil conservation model.

First-level land categories	Second-level land categories	lucode	usle_c	usle_p
Cultivated land	Paddy field	11	0.217	0.20
	Dry land	12	0.291	0.45
Forest land	Woodland	21	0.086	1.00
	Shrub land	22	0.156	1.00
	Sparse forest land	23	0.376	1.00
	Other forest land	24	0.166	0.15
Grassland	High coverage grassland	31	0.315	1.00
	Medium coverage grassland	32	0.130	1.00
	Low coverage grassland	33	0.373	1.00
Water	Rivers and canals	41	0.000	0.00
	Lakes	42	0.000	0.00
	Reservoirs and ponds	43	0.000	0.00
	Beaches	46	0.411	1.00
Construction land	Urban	51	0.000	0.00
	Rural residential areas	52	0.000	0.00
	Industrial and mining construction land	53	0.000	0.00
Unused land	Swamp	64	0.429	1.00
	Barren land	65	1.000	1.00
	Bare rocky gravel land	66	1.000	1.00

usle_c: The USLE vegetation cover and crop management factor, which measures the effect of vegetation cover and management on the inhibition of soil erosion. usle_p: The USLE conservation practice factor, which refers to the ratio of soil loss with support practices (such as contouring, strip cropping, or terracing) to the soil loss with straight-row farming up and down the slope.

(iv) Nitrogen export (NE)

The water purification function refers to the ability of aquatic environments to adsorb, transform, and biologically absorb pollutants through a series of physical and biochemical processes, thereby partially or fully restoring the ecological function of the water body to its original state. In this study, the NE service is assessed using the Nutrient Delivery Ratio model from InVEST, which estimates the removal of pollutants such as nitrogen (N) and phosphorus (P) from runoff by vegetation and soil, and reflects its contribution to water quality purification through the final output of sub-watersheds. Higher outputs of N and P indicate poorer water purification service function [9,15]. Due to data availability issues, this study uses nitrogen output to represent the strength of regional water purification capacity [16]. The nitrogen output per pixel is calculated based on the sum of the product of surface nitrogen load and subsurface nitrogen load with their respective nitrogen output ratios. The total nitrogen output for the entire area is the sum of nitrogen outputs across all pixels. This process simulates the spatial distribution of nitrogen nutrients. The calculation formula is as follows:

$$X_{\mathrm{export}_{tot}} = \sum_i (\mathrm{load}_{\mathrm{surf,i}} \times \mathrm{NDR}_{\mathrm{surf,i}} + \mathrm{load}_{\mathrm{subs,i}} \times \mathrm{NDR}_{\mathrm{subs,i}}) \quad \text{(S11)}$$

Where $X_{export_{tot}}$ is the total nutrient export in the study area; $load_{surf,i}$ and $load_{subs,i}$ are the local runoff potential of each pixel i in surface and subsurface runoff, respectively. $NDR_{surf,i}$ and $NDR_{subs,i}$ defined the nutrient delivery factors of each pixel i in surface and subsurface runoff, respectively. The biophysical coefficient table is shown in Table S5 [17]. The model validation mainly uses similar evaluation cases [7] for comparison.

Table S5. Biophysical coefficients table for the Nutrient Delivery Ratio module [7].

First-level land categories	Second-level land categories	lucode	Load_n	eff_n	crit_len_n	Load_p	eff_p	crit_len_p	proportion_subsurface_n
Cultivated land	Paddy field	11	11	0.25	25	11	0.25	25	0.5
	Dry land	12	11	0.25	25	11	0.25	25	0.5
Forest land	Woodland	21	1.8	0.8	150	1.8	0.8	150	0
	Shrub land	22	1.8	0.8	150	1.8	0.8	150	0
	Sparse forest land	23	1.8	0.8	150	1.8	0.8	150	0
	Other forest land	24	1.8	0.8	150	1.8	0.8	150	0
Grassland	High coverage grassland	31	4	0.4	300	4	0.4	300	0
	Medium coverage grassland	32	4	0.4	300	4	0.4	300	0
	Low coverage grassland	33	4	0.4	300	4	0.4	300	0
Water	Rivers and canals	41	0.001	0.05	15	0.001	0.05	15	0
	Lakes	42	0.001	0.05	15	0.001	0.05	15	0
	Reservoirs and ponds	43	0.001	0.05	15	0.001	0.05	15	0
	Beaches	46	0.001	0.05	15	0.001	0.05	15	0
Construction land	Urban	51	7.5	0.05	10	7.5	0.05	10	0
	Rural residential areas	52	7.5	0.05	10	7.5	0.05	10	0
	Industrial and mining construction land	53	7.5	0.05	10	7.5	0.05	10	0
Unused land	Swamp	64	4	0.05	5	4	0.05	5	0
	Barren land	65	4	0.05	5	4	0.05	5	0
	Bare rocky gravel land	66	4	0.05	5	4	0.05	5	0

load_n / load_p and eff_n / eff_p represent the nutrient load and retention efficiency for each land use classification. Crit_len_n (in meter): The distance over which a small area of land is assumed to retain nutrients at maximum capacity. proportion_subsurface_n: The proportion of dissolved nutrients relative to the total amount of nutrients, expressed as a ratio between 0 and 1.

(v) Water yield (WY)

Based on the principle of water balance, the InVEST water yeild module calculates the difference between the precipitation and the actual evapotranspiration as the water yeild [18]. The calculation formula is as follows:

$$Y_{(x)} = (1 - \frac{AET_{(x)}}{P_{(x)}}) \times P_{(x)} \quad \text{(S12)}$$

where $Y_{(x)}$, $AET_{(x)}$, and $P_{(x)}$ represent the average annual water yield, annual actual evapotranspiration, and annual precipitation (mm) of grid x, respectively.

The quantitative relationship between precipitation and actual evapotranspiration was calculated by the Budyko hydrothermal coupling equilibrium equation, taking into account the process parameters involved in evapotranspiration, such as precipitation, underlying surface cover type, and soil water content. The calculation formula is as follows:

$$\frac{AET_{(x)}}{P_{(x)}} = \frac{1+\omega_{(x)}R_{(x)}}{1+\omega_{(x)}R_{(x)}+\frac{1}{R_{(x)}}} \quad \text{(S13)}$$

$$\omega_{(x)} = Z\frac{AWC_{(x)}}{P_{(x)}} \quad \text{(S14)}$$

$$R_{(x)} = \frac{K_{(x)}ET_{0(x)}}{P_{(x)}} \quad \text{(S15)}$$

$$ET_{0(x)} = \alpha \times RA \times (T_{avg} + \beta) \times (TD + \gamma) \quad \text{(S16)}$$

$$PAWC = 54.509 - 0.132sand - 0.003(sand)^2 - 0.055(silt)^2 - 0.738clay + 0.007(clay)^2 - 2.688OM + 0.501(OM)^2 \quad \text{(S17)}$$

where $R_{(x)}$ is the Budyko dryness index of the grid x (dimensionless); $ET_{0(x)}$ is the potential evapotranspiration in the grid (mm), calculated using the Modified-Hargreaves formula，α、β、γ is the equation parameter, determined according to the previous research; RA is the extraterrestrial solar radiation (mm·yr^{-1}); $\omega_{(x)}$(dimensionless) is an empirical parameter, which is used to describe the climate-soil properties, $K_{(x)}$ is the evapotranspiration coefficient of the grid x corresponding to the vegetation type, which is determined by referring to the vegetation transpiration coefficient table provided by FAO and previous research; $AWC_{(x)}$ is the available water content of vegetation, calculated according to soil properties, $sand$、$silt$、$clay$ is soil sand, silt, and clay content (%); Z (dimensionless) is the Zhang coefficient, which is determined according to the seasonal law of precipitation area and the characteristics of the catchment area in the study. The spatial resolution of all the above data is 30m × 30 m. The root depth for each vegetation type [19], flow rate coefficient, and vegetation evapotranspiration coefficient [13,20] are shown in Table S6.

Table S6. Water supply service parameters [20].

First-level land categories	Second-level land categories	lucode	root_depth	LULC_veg	Kc
Cultivated land	Paddy field	11	1800	1	0.7
	Dry land	12	1800	1	0.65
Forest land	Woodland	21	7000	1	1
	Shrub land	22	7000	1	0.95
	Sparse forest land	23	7000	1	0.93
	Other forest land	24	7000	1	0.93
Grassland	High coverage grassland	31	1500	1	0.85
	Medium coverage grassland	32	1500	1	0.65

	Low coverage grassland	33	1500	1	1
	Rivers and canals	41	1000	0	1
	Lakes	42	1000	0	0.3
Water	Reservoirs and ponds	43	1000	0	0.2
	Beaches	46	1000	0	1
	Urban	51	500	0	0.3
	Rural residential areas	52	500	0	0.2
Construction land	Industrial and mining construction land	53	500	0	0.3
	Swamp	64	500	1	1
	Barren land	65	500	0	0.2
Unused land	Bare rocky gravel land	66	500	0	0.2

LULC_veg: Indicates whether a land use type is covered by vegetation, with 1 representing vegetation coverage and 0 representing no vegetation coverage. root_depth: Refers to the maximum root depth of the soil for each land use type, which is the deepest soil layer that plant roots can reach. Kc: Represents the vegetation canopy coefficient for each land use type, which reflects the capacity of vegetation for evapotranspiration.

2. Characteristics of ES bundles

At the grid scale, the characteristics of the six ES bundles are as follows.

(1) Key synergetic bundle (B1): This bundle was primarily located in the northern, central, and western mountainous regions, covering 19.21%, 1.39%, and 21.47% of the study area in 2010, 2015, and 2020, respectively (Figure 9a and Figure 9c). It exhibited spatial synergy with high levels of CS, HQ, SC, and WY (Figure 9b).

(2) CS bundle (B2): This bundle, which occupied the largest proportion, was mainly found in transition zones between different bundles, interspersed with forested and grassland areas. It covered 45.07%, 37.83%, and 41.04% of the study area in 2010, 2015, and 2020, respectively (Figure 9a and Figure 9c). It was notably characterized by a high supply of CS (Figure 9b).

(3) CS-SC-WY synergy bundle (B3): This bundle was primarily located in transition areas between different bundles, interspersed with grassland, covering 1.19%, 17.95%, and 18.01% of the study area in 2010, 2015, and 2020, respectively (Figure 9a and Figure 9c). It was distinguished by high spatial synergy in CS, SC, and WY (Figure 9b).

(4) City bundle (B4): This bundle was primarily situated in the eastern built-up and water areas, covering 2.94%, 3.43%, and 3.46% of the study area in 2010, 2015, and 2020, respectively (Figure 9a and Figure 9c). The supply of ESs in this bundle was minimal, serving mainly as a beneficiary area in the Lishui River Basin (Figure 9b and Figure 9c).

(5) CS-WY synergy bundle (B5): This bundle was primarily distributed in the central and western regions, with a mix of cropland and grassland, covering 17.08%, 24.51%, and 1.14% of the study area in 2010, 2015, and 2020, respectively (Figure 9a and Figure 9c). It was characterized by the spatial synergy of high CS and high WY (Figure 9b).

(6) CS-NE synergy bundle (B6): This bundle was primarily found in the eastern and central regions, featuring landscapes of cropland, construction land, and water areas. It covered 14.50%, 14.89%, and 14.88% of the study area in 2010, 2015, and 2020, respectively

(Figure 9a and Figure 9c). This bundle was distinguished by the spatial synergy between high CS and high NE (Figure 9b).

At the sub-watershed scale, the characteristics of the four ES bundles are as follows.

(1) CS-WY synergy bundle (B-1): This bundle, occupying the largest proportion, comprised sub-watersheds in the northern and southern hilly areas, predominantly featuring forested and grassland landscapes. It covered 58.47%, 56.63%, and 58.65% of the study area in 2010, 2015, and 2020, respectively (Figure 10a and Figure 10c). It was characterized by a high spatial synergy between CS and WY (Figure 10b).

(2) Key synergetic bundle (B-2): This bundle included sub-watersheds mainly located in the northern and northwestern high-elevation mountainous and hilly regions. It covered 19.93%, 18.29%, and 18.29% of the study area in 2010, 2015, and 2020, respectively (Figure 10a and Figure 10c). It was distinguished by the spatial synergy of multiple ecosystem services, including high CS, high HQ, high SC, and high WY (Figure 10b).

(3) Downstream city bundle (B-3): This bundle comprised sub-watersheds primarily situated in the northeastern and eastern downstream areas of the river, characterized by flat topography and abundant water resources. It was dominated by cropland, urban construction, and water areas, covering 4.94%, 4.95%, and 18.11% of the study area in 2010, 2015, and 2020, respectively (Figure 10a and Figure 10c). This bundle offered limited ecosystem services, with the exception of a notable supply of NE (Figure 10b).

(4) CS synergy bundle (B-4): This bundle included sub-watersheds predominantly found in flat tillage regions with extensive and contiguous croplands. It covered 16.65%, 20.13%, and 4.95% of the study area in 2010, 2015, and 2020, respectively (Figure 10a and Figure 10c). It was characterized by strong spatial synergy in high CS (Figure 10b).

At the county scale, the characteristics of the four ES bundles are as follows.

(1) CS-WY synergy bundle (B-a): This bundle consisted of the county mainly located in the northeastern and eastern mountainous areas, covering 51.31%, 24.74%, and 24.74% of the study area in 2010, 2015, and 2020, respectively (Figure 11a and Figure 11c). This bundle presented the spatial synergistic characteristics of high CS and high WY (Figure 11b).

(2) CS bundle (B-b): This bundle, which makes up the largest proportion, encompassed the county situated primarily in the central and southern mountainous and hilly regions. The primary land use types were forested land and grassland, accounting for 37.34%, 56.68%, and 56.68% of the study area in 2010, 2015, and 2020, respectively (Figure 11a and Figure 11c). This bundle was distinguished by a significant supply of high CS (Figure 11b).

(3) Downstream city bundle (B-c): This bundle encompassed the county located mainly in the northeastern and eastern areas with flat topography and abundant water resources. It featured extensive and contiguous croplands and was dominated by cropland, urban construction, and water areas. It covered 11.02%, 18.44%, and 18.44% of the study area in 2010, 2015, and 2020, respectively (Figure 11a and Figure 11c). This bundle offered limited ecosystem services, except for a notable supply of NE (Figure 11b).

(4) HQ-SC-WY synergy bundle (B-d): This bundle included the county situated in the northern mountainous areas, with a relatively small land use area, covering 0.33%, 0.14%, and 0.14% of the study area in 2010, 2015, and 2020, respectively (see Figure 11a and Figure 11c). It was characterized by high spatial synergy in HQ, SC, and WY (refer to Figure 11b).

3. Proportion of land use types

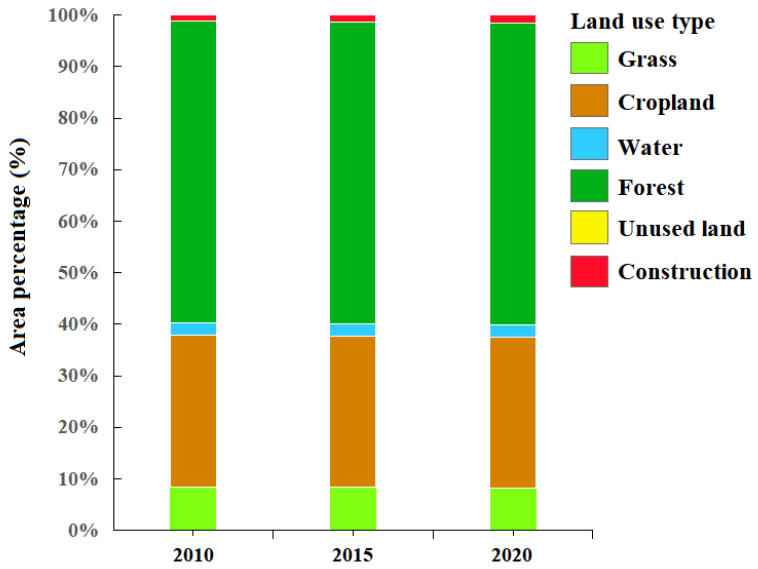


Figure S1. Area percentage of each land use type from 2010 to 2020.

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